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INVESTIGATION OF THE EFFECTS OF WIND WAVES ON A TEMPERATURE GRADIENT IN A WAVE TANK

THOMAS HERBERT CRAMER

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INVESTIGATION OF THE EFFECTS OF WIND WAVES

ON A TEMPERATURE GRADIENT IN A WAVE TANK

by

Thomas Herbert Cramer
Lieutenant, United States Navy
B.S., Colorado University, 1963

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN OCEANOGRAPHY

from the

NAVAL POSTGRADUATE SCHOOL
June 1968

Signature of Author Thomas H. Cramer.

Approved by Theodore Green III
Thesis Advisor

G. J. Haltiner
Chairman, Department of Oceanography

W. F. Koehler for R. F. Rinehart
Academic Dean

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ABSTRACT

An investigation was undertaken to examine the effects of wind waves upon a temperature gradient in a wave tank. The gradient was created by heating the surface water and cooling the bottom water. Temperature measurements were made with thermometers and a thermistor. The wind was measured with a pitot tube anemometer. The wind waves created a thermocline, and there was an indication of a linear correlation between the depth of the thermocline and the wind speed, which was similar to previous open-ocean work. A heat budget calculation was made, and it was found that the amount of heat in the water column remained almost constant.

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The advice and assistance of Professor Theodore Green, both scientifically and editorially, were of great aid in the writing of this thesis. Without the electronic skill and advice so generously given by LCDR Jack McMillan, many of the measurements made during the course of this investigation would have been impossible.

INTRODUCTION

Thermoclines[1] exist throughout the world's oceans and are found to vary greatly in depth and intensity. They are found almost at the surface and at depths up to several hundreds of feet. There is a great deal of empirical evidence to indicate that wind waves play an important if not major role in the depth of the thermocline. The data shows in general that the stronger the wind, the deeper the thermocline. Experimental conditions are impossible to control in the open ocean so that results are often hard to interpret. A model experiment might be useful in isolating important parameters.

The purpose of this study was to set up a temperature gradient in a body of water, and then investigate the consequences of various surface winds on the gradient (e.g. , formation of a thermocline, if any, and depth of mixing). A secondary objective was to make heat budget calculations by comparing the amount of heat present in the water with no wind to the amount present under various wind conditions.

A wave tank was used to carry out the investigation (Figure 1). The temperature gradient was created by cooling the bottom of the tank with tap water passed through a relatively shallow aluminum container constructed to fit snugly in the bottom, and heating the surface by means of common electric fans. Temperature measurements were made with a series of thermometers and a thermistor. The wind was measured with a pitot tube anemometer and wave height was obtained using a resistance-wire gauge.

---

[1]A thermocline is a narrow region in a vertical water column where the vertical temperature gradient is large compared to overlying and underlying gradients.

BACKGROUND

Many field studies have been conducted on the formation and movement of thermoclines at ocean station "P" and at other locations (see, for example, Tabata, Boston, and Boyce, 1965), but the closest related model work was done by Cromwell (1965) just before his death.

The purpose of Cromwell's experiment was to ascertain whether or not a pycnocline (the region where the vertical density gradient is large compared with overlying and underlying gradients) could be formed by introducing turbulent energy near the surface, and to gain insight into the formation and maintenance of the pycnocline.

Cromwell carried out his experiment in a small tank in which he introduced turbulent energy by driving an iron mesh up and down in simple harmonic motion. He created a visible density structure by introducing the lightest (least colored, freshest) water into the tank first, and then successively introducing denser (more deeply colored, saltier) water near the bottom through a siphon. He then agitated the mixture near the surface with the mesh and from time to time withdrew samples from various parts of the tank and determined their density.

The results were as expected. A pycnocline formed almost immediately and descended in the tank as the surface agitation continued. An increase of the frequency of the agitation drove the pycnocline down faster. Further, if the mesh was oscillated close to the bottom a pycnocline would form above the mesh. With the mesh at an intermediate depth, pycnoclines formed both above and below.

Cromwell believed his results analogous to events in the ocean in that all the ocean data referred to above indicates that the stronger the wind, the deeper the pycnocline. One criticism of the experiment

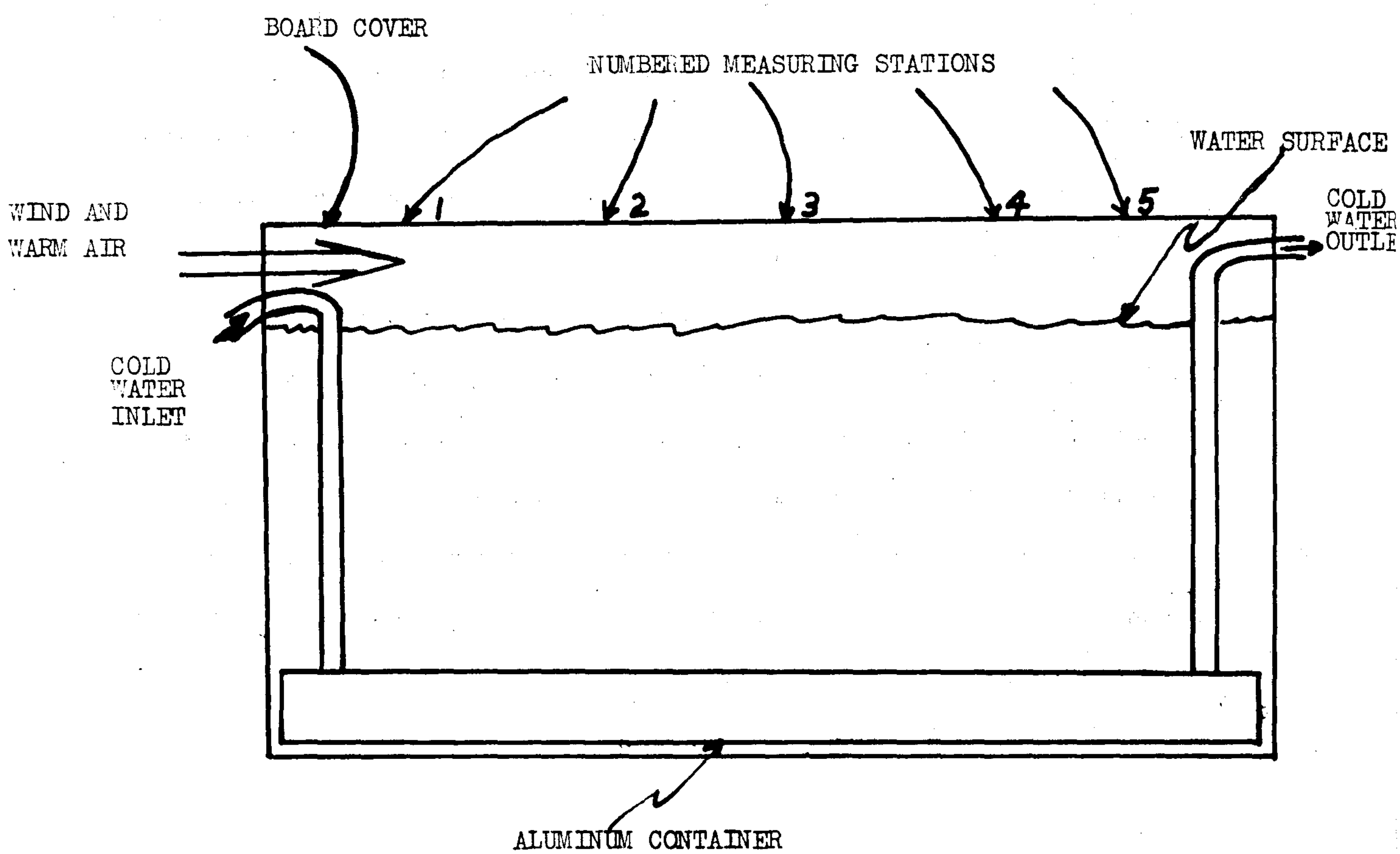
was made by Eckart, who thought the turbulence spectra in the model and ocean may be dissimilar.

Since the source of energy used by the author to create the turbulence is wind, it is felt that in this case, Eckart's criticism is less valid. The scale of the experiment could cause the wave spectrum to be different from that of the open ocean, but it is believed that the wind-induced turbulence approaches more closely that in the open ocean than did Cromwell's mesh-generated turbulence.

Tabata, et. al. examined bathythermographic and wind speed data collected at station "P" during April through August of the years 1956 through 1959 for relationships between the depth of the isothermal surface layer and the wind speed. They found a linear correlation between the shallowest thermocline and the mean wind speed averaged 12 hours in advance of the bathythermographic observations. It was hoped to find a similar result in this model study.

FIGURE ONE

DIAGRAM OF WAVE TANK



EQUIPMENT

The major piece of equipment used was a wave tank built by the National Engineering Science Company (Figure 1). The dimensions of the water containing area are: 27 inches deep, 48 inches wide, and 84 inches long. For the purposes of this experiment, a partition was inserted in the tank reducing the width to 12 inches, and the water depth was set at 21 inches to allow the lip of the wind baffle described below to be just above the water.

The bottom water was cooled by running tap water through an aluminum container which was constructed to fit snugly in the bottom of the tank. The tap water varied from 59°F to 63°F depending on the air temperature. Normally the circulating tap water would cool the bottom water in the tank to about 4°F above the tap water temperature.

The wind source was built into the wave tank, and consisted of an 8-inch diameter centrifugal-type fan powered by a small electric motor. The wind was channeled through ducts finally opening through a 4 by 12 inch baffle over the water surface at one end of the long axis of the tank. It was possible to vary the wind speed from zero to about 700 cm/sec. The wind was contained above the water by putting a 12 by 80 inch board four inches above the water surface. Because of leakage, the speed varied down the channel, with the wind speed at the end about one third the wind speed at the source.

The surface water was heated by forcing warm air to pass over it. This was accomplished by putting two common electric room heaters behind the fan and then turning the fan to a low speed to circulate the warm air. With this arrangement, air temperatures in the neighborhood of 135°F were created above the water. As in the case of bottom cooling, the exact temperature was a function of room temperature.

DATA COLLECTION

All measurements (except tap-water temperature, which was taken at the discharge) were taken at five horizontal locations, and at various vertical locations depending on the information desired. The horizontal locations (numbered 1 to 5) were spaced at 15-inch intervals down the long axis of the tank to the end, beginning with number 1 at the wind source. Air temperature and wave height were recorded at these locations; water temperature and current measurements were taken at the surface and various depths. Sufficient information was obtained to determine mean current profiles and temperature structure.

The water temperature measurements were made in two different ways. Eight thermometers were suspended approximately three inches apart by strings from the surface to the bottom, and a continuous profile was obtained by raising a thermistor at a fairly constant rate from the bottom to the surface. The thermistor was an exposed oxide junction type and the signal was sent to a Mosley 7100B Strip Recorder. The thermistor was calibrated by putting it as near as possible to the top (warmest) thermometer, noting the reading on the recorder, then putting it near the bottom (coolest) thermometer and again noting the reading on the recorder. The thermistor was assumed to be linear in the temperature range of the experiment (60°F to 85°F). This assumption was originally made by examination of the calibration curves. Random checks indicated that the assumption was valid. The response time of the thermistor was in the neighborhood of 50 milliseconds, which is much faster than that of the thermometers. To insure correct thermometer readings, two recordings were generally made with a time separation of a few minutes. The accuracy of the thermometers was about ± 0.3°F. The absolute accuracy

of the thermistor had to be the same because of the calibration technique, but the relative accurace was about $\pm 0.05°F$.

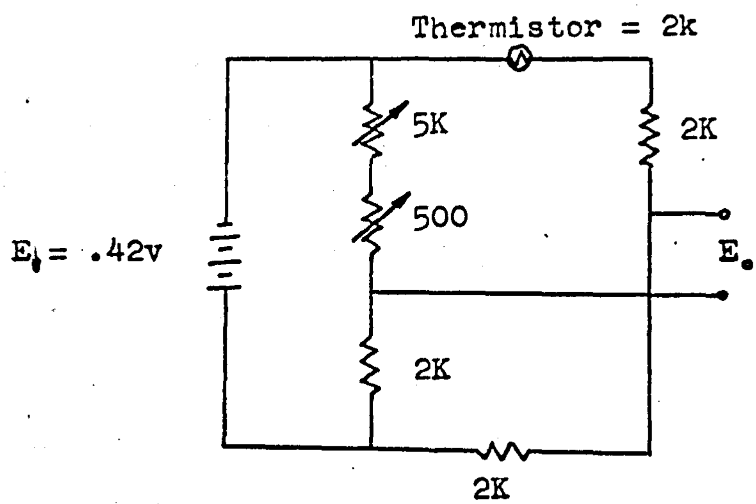
Waves were measured with a resistance-wire gauge constructed from two 0.01-inch diameter stainless steel wires 25 centimeters long and 3 centimeters apart. It had a five-volt twenty-kilohertz power source. The signal was put through a full-wave rectifier to the same recorder as was used for the thermistor. The gauge was calibrated by raising and lowering it a known amount in the water and again noting readings on the recorder. The gauge was assumed to be linear in the range of wave heights observed (0 to 0.75 centimeters). Wiring diagrams of the thermistor and wave gauge are included in Figure 2.

As the work progressed, it became evident that the wind was creating appreciable currents in the tank. The temperature profiles showed that, at the higher wind speeds, the currents were affecting the temperature structure. By observing small particles move in the water, it was apparent that no commercial current meter available would be able to measure these currents because of their small magnitude (less than two cm/sec). In order to gain some idea of the magnitude of the currents, various devices were tried. A small model airplane propeller mounted on a wire proved to be the most sensitive. The propeller was calibrated by drawing it past a known distance in the water and counting the number of revolutions. The device was sensitive enough so that, even at varying speeds, the number of revolutions would be about the same over the given distance. Knowing the number of revolutions over a certain distance and counting the number of revolutions in a given time period, one could calculate the amount of water which had traveled past, and thus compute the current. This crude method of measuring current was fairly accurate ($\pm 25\%$) for currents between one and two cm/sec, but for smaller currents,

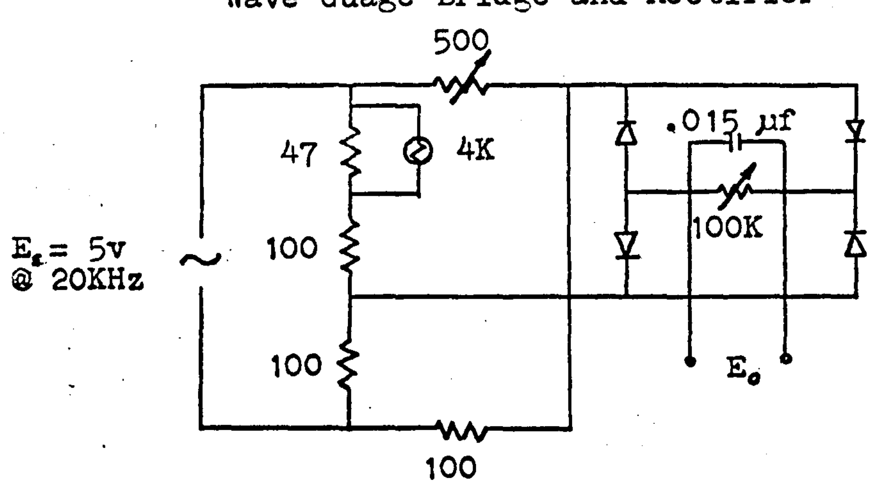
FIGURE 2

WIRING DIAGRAM OF THERMISTOR AND WAVE GAUGE

Thermistor Bridge



Wave Guage Bridge and Rectifier



the inertia of the device was too great, and it was difficult to get the propeller to spin at a uniform rate. When it finally would begin to rotate, it tended to stop with the heavy end down even though it was balanced as well as possible. At these slow speeds, the accuracy is estimated to be $\pm 75\%$.

The wind speed was obtained by using a pitot tube anemometer which measured pressure differences in inches of water. This was converted into velocity by using Bernoulli's equation:

$$V^2 = \frac{2\Delta P}{\rho}$$

where: V = wind speed

ΔP = pressure difference

ρ = air density.

The accuracy of the device is estimated to be $\pm 5\%$.

EXPERIMENTAL PROCEDURE

The experiment was performed several times with the thermometers and once with the thermistor. In all cases when a sufficient temperature gradient was established, the results were almost identical. On a few occasions, it was impossible to create a suitable gradient, apparently because the room temperature was too low, and most of the heat would be lost to the surroundings rather than warming the water.

The general procedure was to create the temperature gradient, and then blow a certain wind (see below) over the surface until a steady-state situation was present. The air and water temperature measurements were taken and the process repeated using a higher wind speed. During the course of the experiments, it became evident that thirty minutes were sufficient for steady-state conditions to be established. To check this, the wind speed was set constant on two occasions and water temperature readings taken every ten to fifteen minutes for a period of about five hours. During both trials, the water temperature structure remained essentially the same after one half hour.

There were two speed controls for the wind, one graduated in units from zero to one hundred and another labeled torque increase. During the experiment, the wind speed was changed using the graduated control, starting at 30 (which had no effect on the vertical temperature structure, but was necessary to carry the heat to the water surface). The speed was increased by units of 10 until 100 was reached, at which time the torque control was turned to full power. Using the pitot tube anemometer, the wind speed was measured at the five stations. The results are displayed in Figure 3.

In Figure 3, the ordinate represents the wind scale units as labeled on the wave tank, and the abscissa is the actual wind speed in cm/sec. There are five curves on the figure representing the wind speed at the different stations. It should be noted that the wind is highest for the station near the wind source (station 1) and that it decreases as the anemometer is moved away from the source. A setting of 30 scale units yields about 150 cm/sec at the source, and 60 cm/sec at the far end of the tank. Likewise, full power yields 700 cm/sec at the source and 270 cm/sec at the far end. In the range of interest, i.e., 30 to 90 scale units, the curves are essentially linear. These curves were used to get actual wind values throughout the experiment.

RESULTS

Figure 4 through 8 show the temperature structure at each station for a representative run. The results of the other runs are very similar, indicating that the experiment is repeatable. The abscissa of each plot is temperature in °F; the ordinate is water depth in inches. There are four curves on each figure representing conditions at wind speeds of from 30 to 60 scale units. At wind speeds above this, the temperature structure becomes almost uniform due to the effects of the wind-induced current. The actual wind speeds and wave heights are indicated on the figures. At the start, the surface is quite warm (about 80°F) and cools rapidly to 67°F near a depth of ten inches. When the speed is increased, a thermocline is developed. As the wind becomes stronger, the thermocline sinks as expected. The pertinent information from the figures is summarized in Table 1.

From Table 1, it can be seen that the strongest gradient (about 10°F/in) exists at station four. This is also in the neighborhood of the highest waves (see below). The deepening of the thermocline with increasing wind speed is displayed in Figure 9 which has thermocline depth in inches plotted vs wind speed in cm/sec for each station. There appears to be a linear correlation between wind speed and thermocline depth, which corresponds to the linear correlation found by Tabata, et. al. in their analysis of station "P" data. It is difficult to make detailed comparisons, however, due to the many unknown scaling factors.

Figures 4 through 8 show that the thermocline deepens with distance from the source (despite the fact that the wind also decreases with distance from the source). For example, at station 1, with a wind of 325 cm/sec, the thermocline is 5 inches deep. At station 5, under the same

wind scale units, the wind has decreased to 120 cm/sec and the thermocline is about 8 inches deep. This indicates that wind-induced currents are not negligible, and that the heated surface water concentrates and sinks at the leeward end of the tank.

This is borne out at higher wind speeds (when the temperature structure becomes almost uniform) where the currents are strong enough to be measured (Figure 11). The concentration of warmer water at the leeward end is also shown in Figure 10, where isotherms are plotted. The bunching of isotherms at the thermocline is also apparent. Because of this horizontal distance effect, it is difficult to interpret the data in terms of the open ocean. However, the model might suffice for oceanic situations where there is a vertical boundary downwind.

Figures 4 through 8 suggest that there is a large loss of heat from the water column as the wind is increased. To investigate this, a crude heat budget calculation was made by taking the average temperature at one-inch intervals, calculating the heat present and then summing over the water column.

The maximum variation with wind speed turned out to be less than 1%, which implies that very little heat was lost. For example, at station 3, the amount of heat in a unit-area column at the start was 838 calories; with a wind of 175 cm/sec, 845 calories; with a wind of 220 cm/sec, 840 calories; with a wind of 270 cm/sec, 843 calories; and at full power, 833 calories.

The wind-induced currents were too small to measure until the wind speed was increased to 70 scale units, which also was the speed necessary to create large enough currents to effectively mix the water and destroy the thermocline. An example of the current profile for a wind of 90 scale units is given in Figure 11, where the current vectors are plotted

throughout the tank. Near the wind source, the motion was quite random, and no mean direction could be found.

The relationship between wind speed and wave height was also investigated (Figure 12). Here the wind speed is the abscissa and the wave height the ordinate. The four curves represent the various locations where the wave height was recorded. In general, the wave height increases downwind. This however, cannot account for the deepening of the thermocline at the leeward end. At wind speeds at which the downwind deepening of the thermocline is evident, the wave height is not the largest at the leeward end. In Figure 13, wave height is plotted against distance from the source for wind speeds at which the thermocline existed. The highest waves occur about two thirds of the way down the tank.

TABLE 1

STRENGTH AND DEPTH OF THERMOCLINE

Station #	Wind Speed (cm/sec)	Depth of Thermocline (in)	dT/dz(°F/in)
1	150	none	0.0
1	250	2.5	1.2
1	325	5.0	1.1
1	425	none	0.0
2	140	none	0.0
2	220	3.0	6.0
2	290	6.0	2.0
2	375	13.0	1.2
3	125	none	0.0
3	170	3.0	8.0
3	225	6.5	4.0
3	255	11.0	1.1
4	110	none	0.0
4	135	2.5	10.0
4	175	8.0	4.0
4	200	11.5	3.0
5	60	none	0.0
5	90	3.0	0.0
5	125	8.5	2.0
5	155	13.0	1.5

FIGURE 3. WIND SPEED VS SCALE UNITS

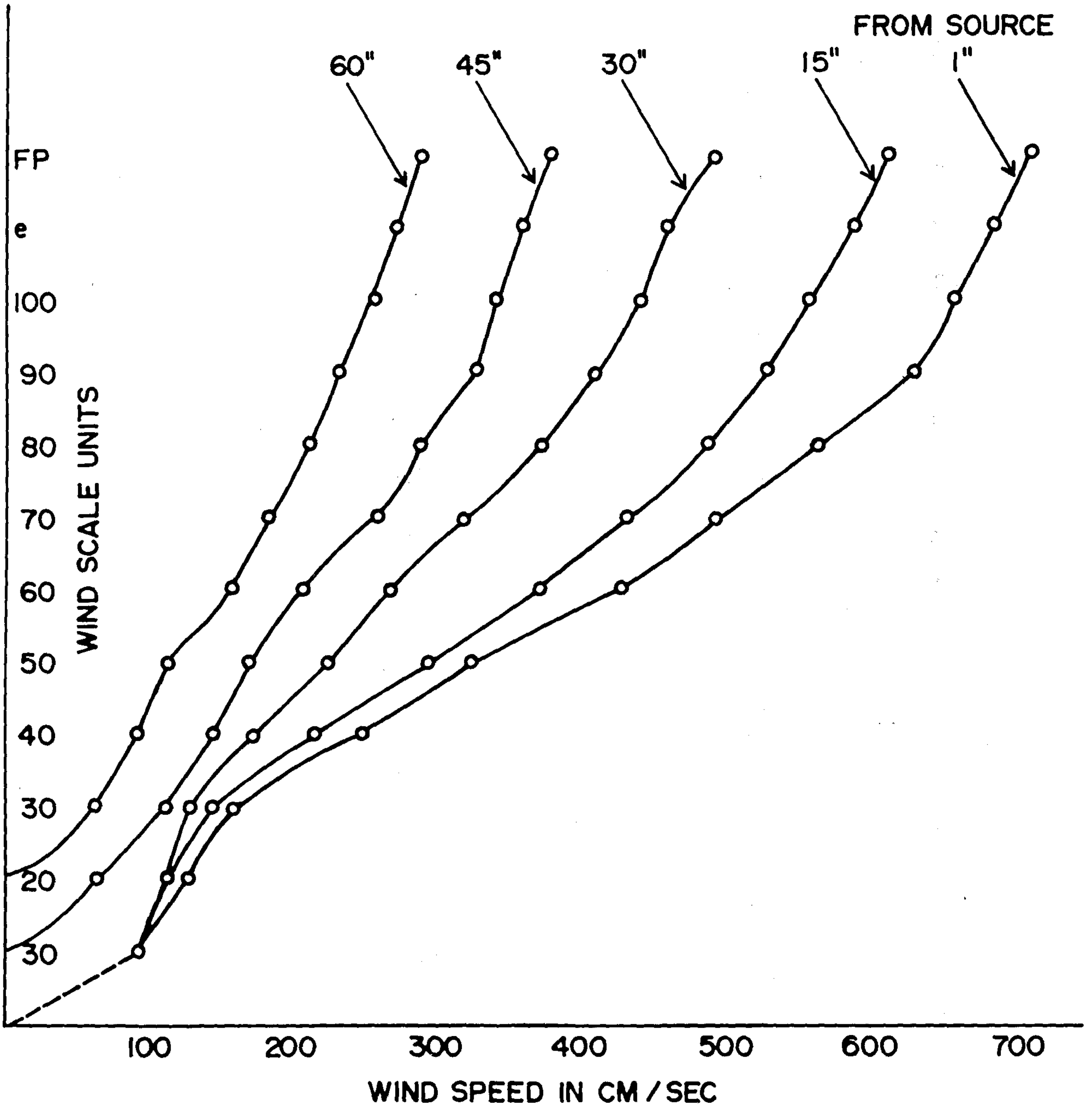


FIGURE 4. STATION 1

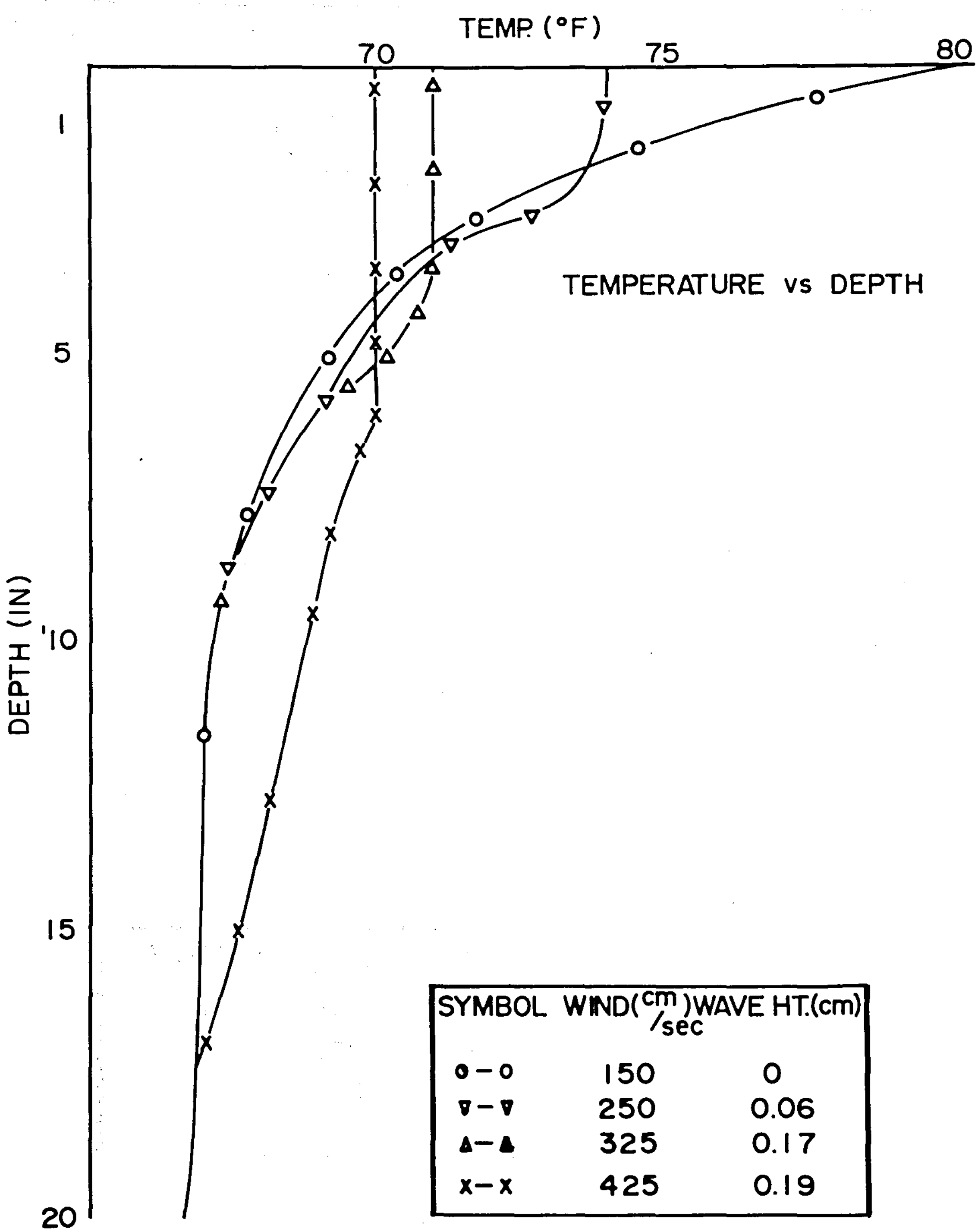
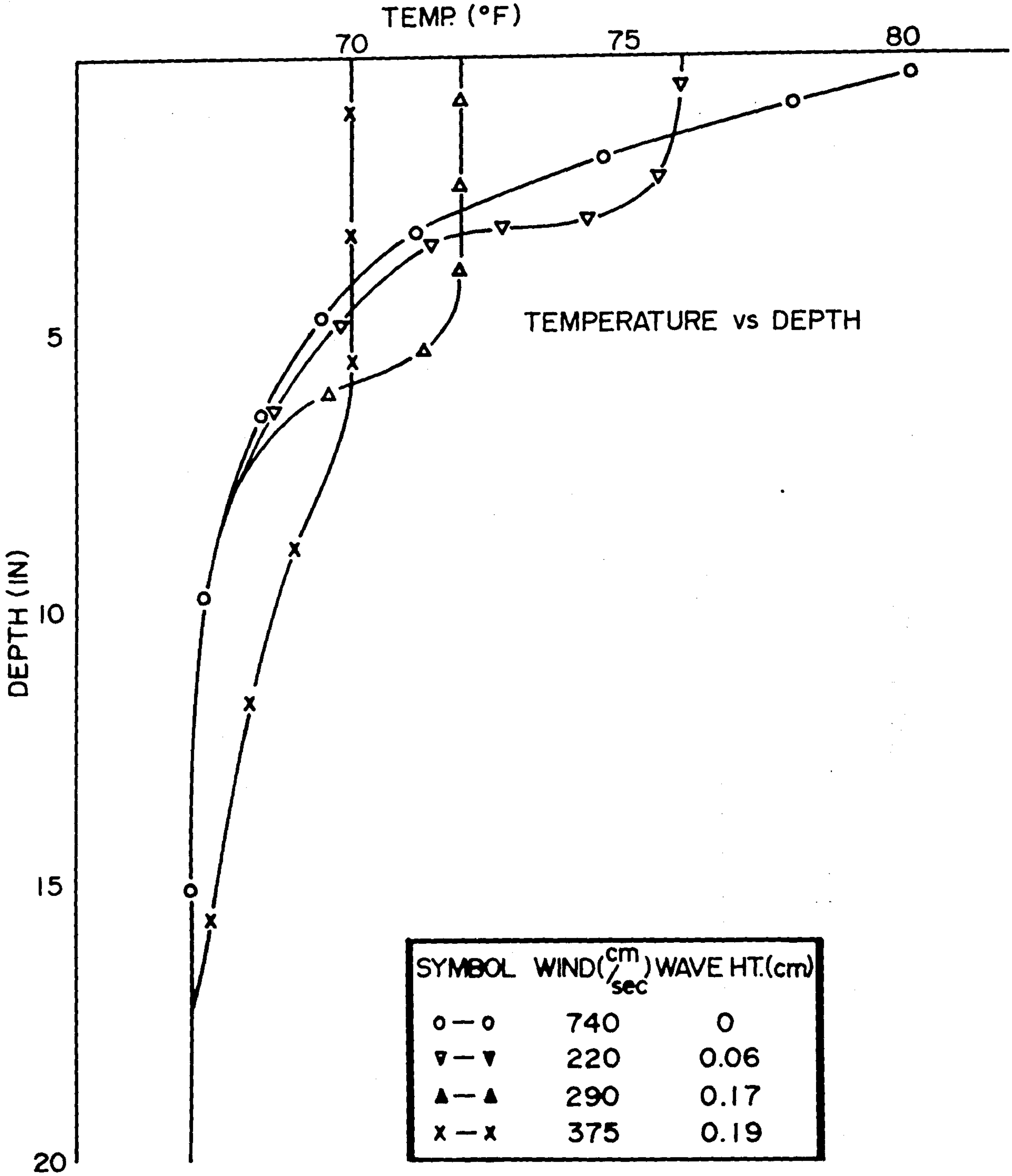


FIGURE 5. STATION 2



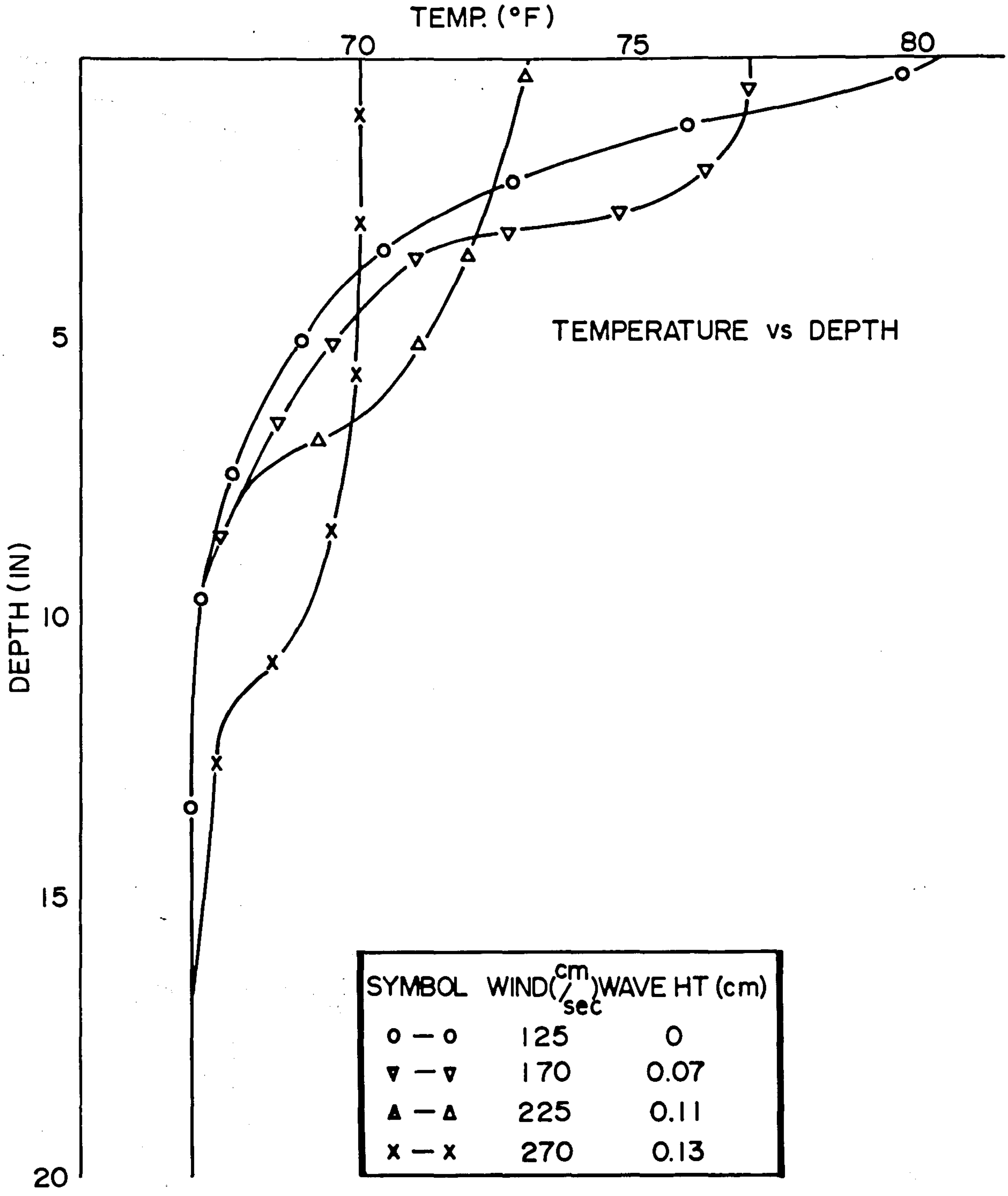

TEMP. (°F)
70
75
80
TEMPERATURE vs DEPTH
DEPTH (IN)
5
10
15
20
SYMBOL WIND(cm/sec) WAVE HT (cm)
o — o 125 0
▽ — ▽ 170 0.07
△ — △ 225 0.11
x — x 270 0.13

FIGURE 7. STATION 4

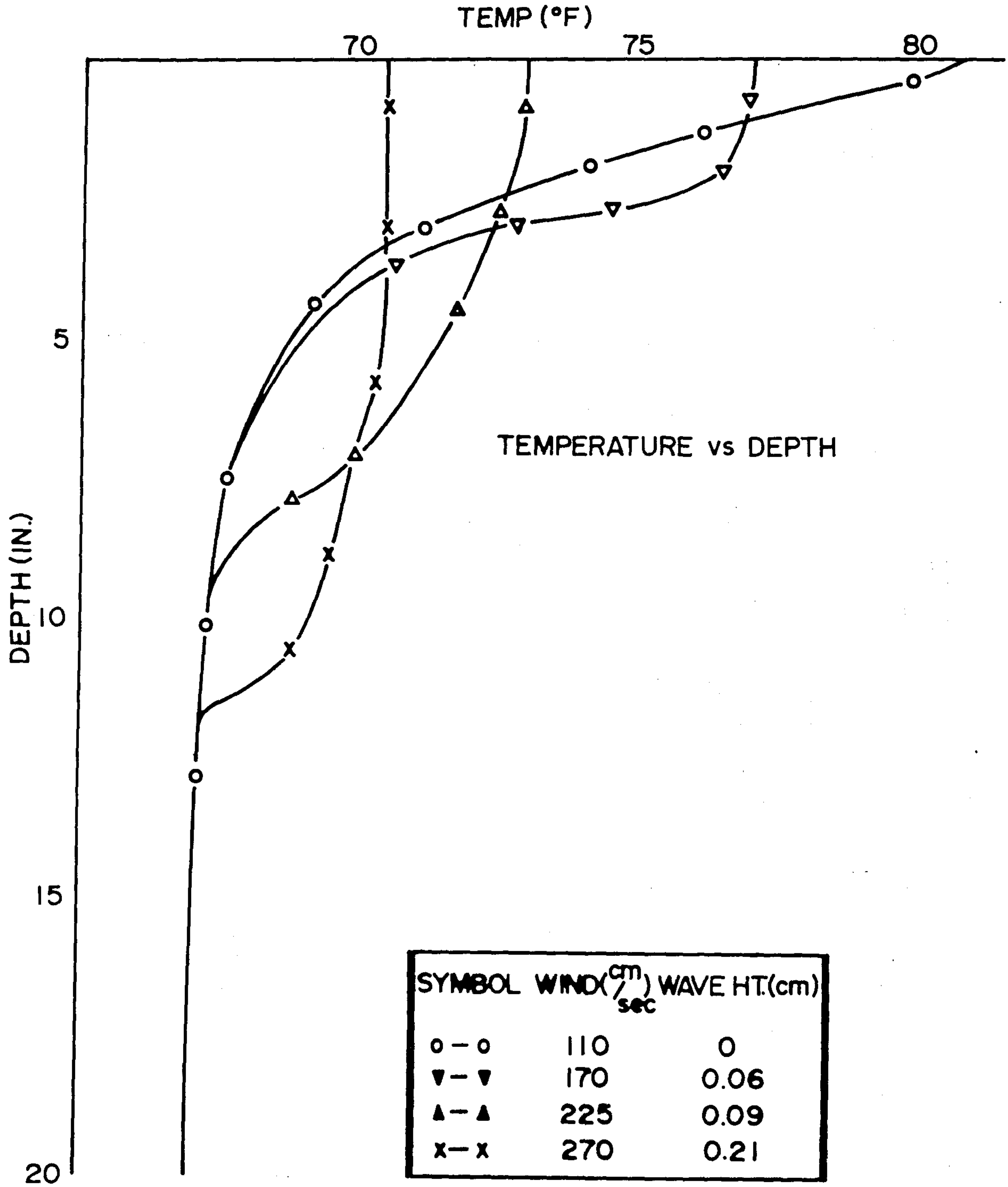


FIGURE 8. STATION 5

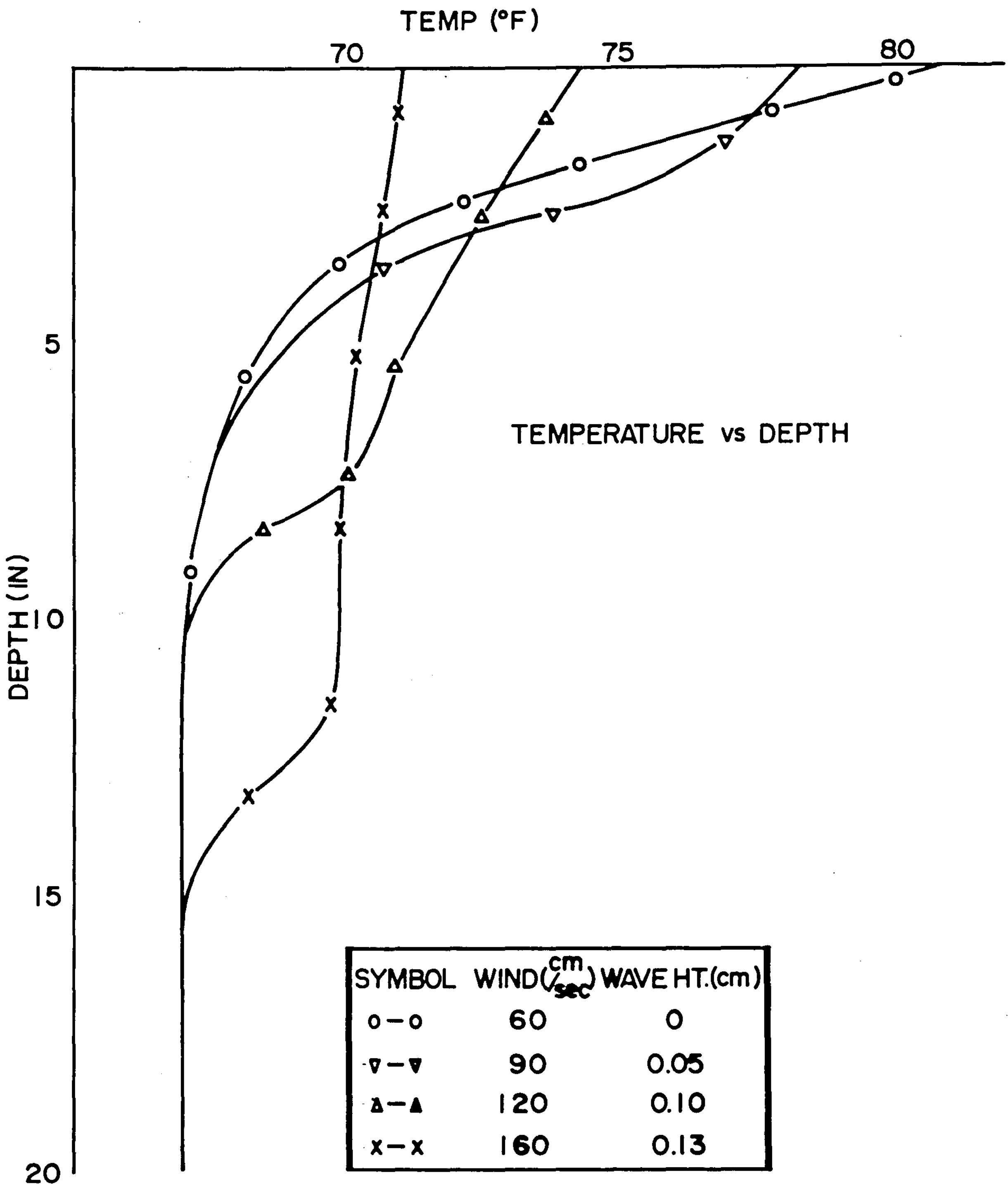
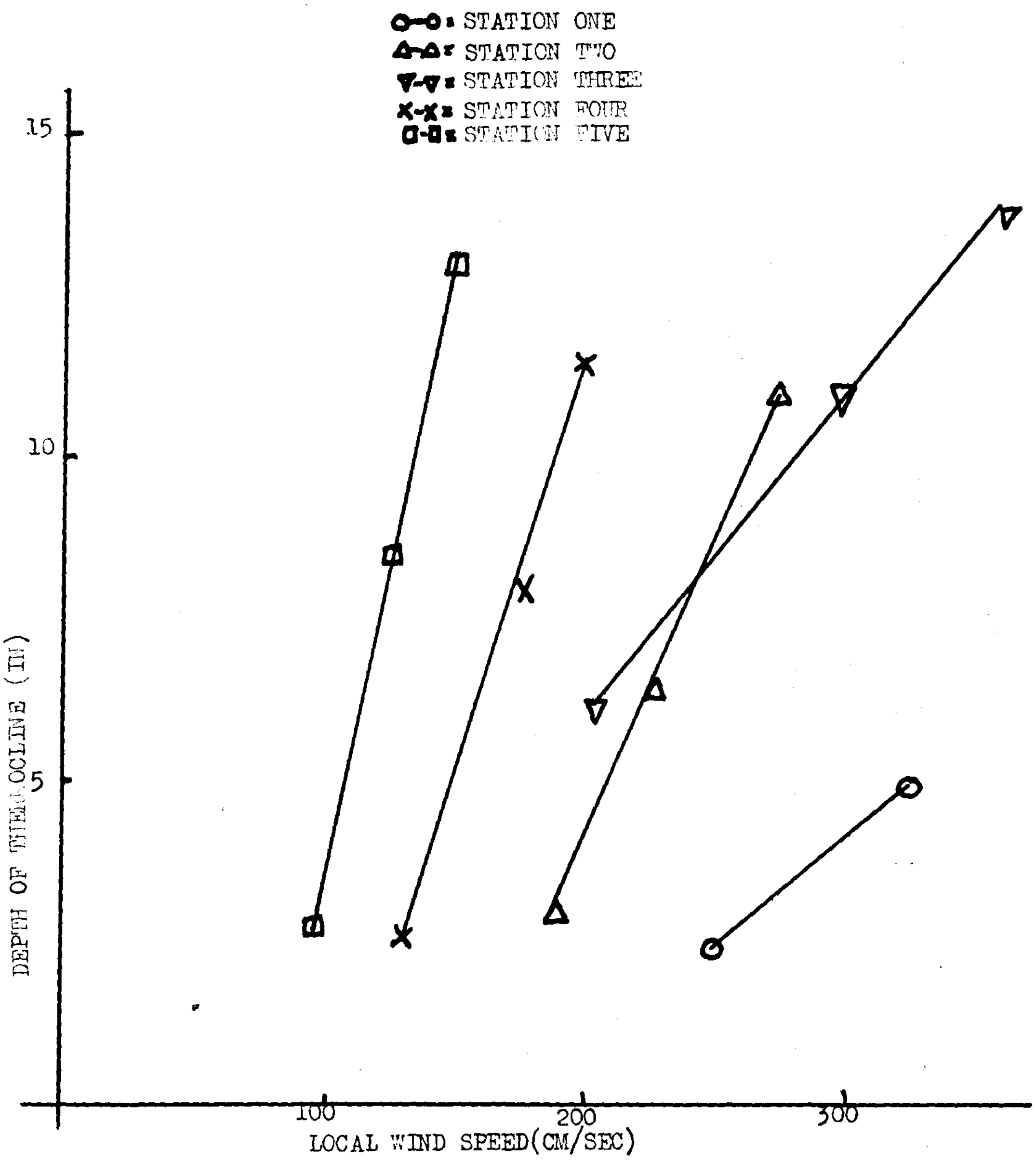
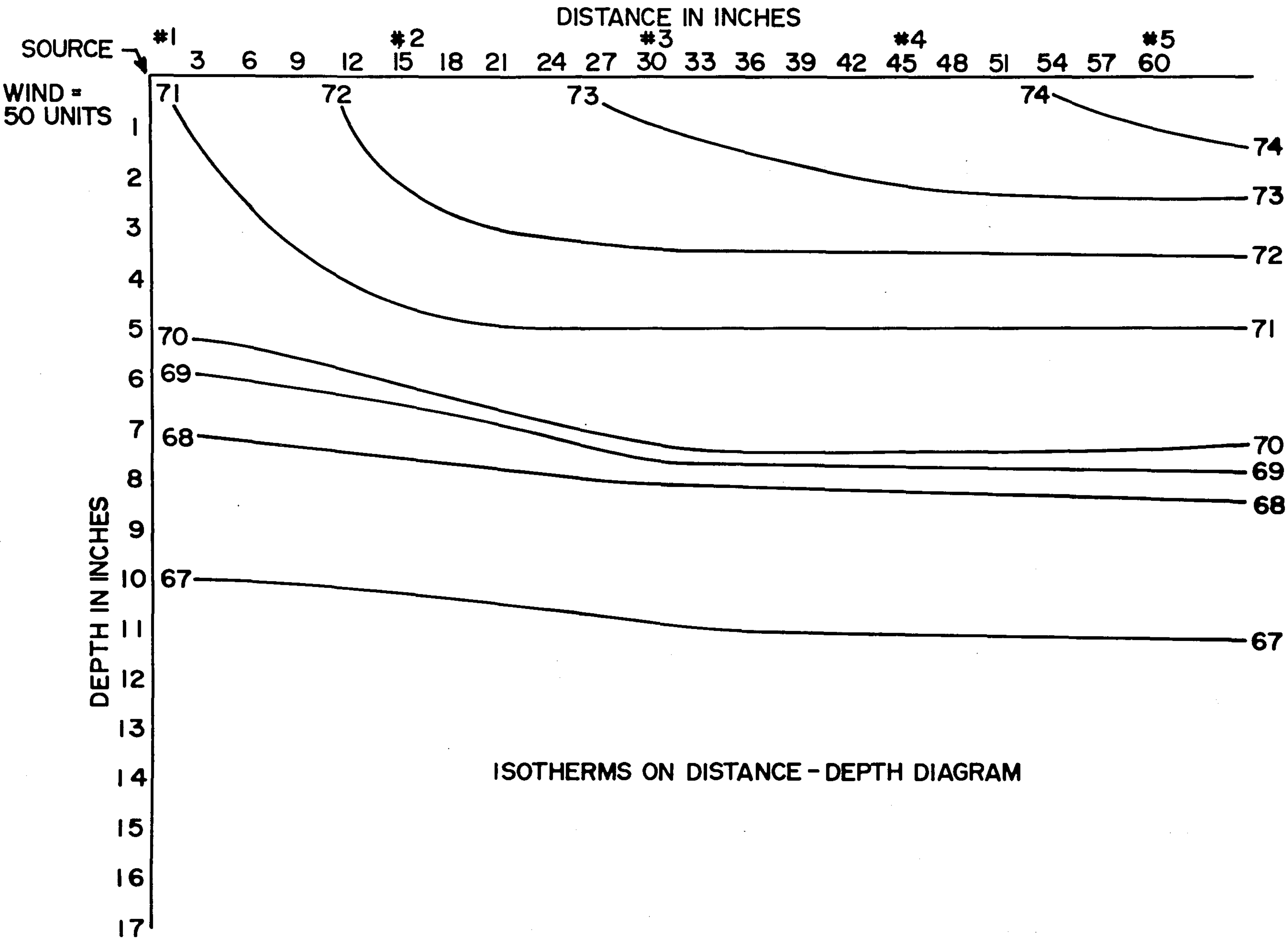


FIGURE 9. THERMOCLINE DEPTH VS WIND SPEED





ISOTHERMS ON DISTANCE - DEPTH DIAGRAM

FIGURE 10

FIGURE 11. CURRENT PROFILE

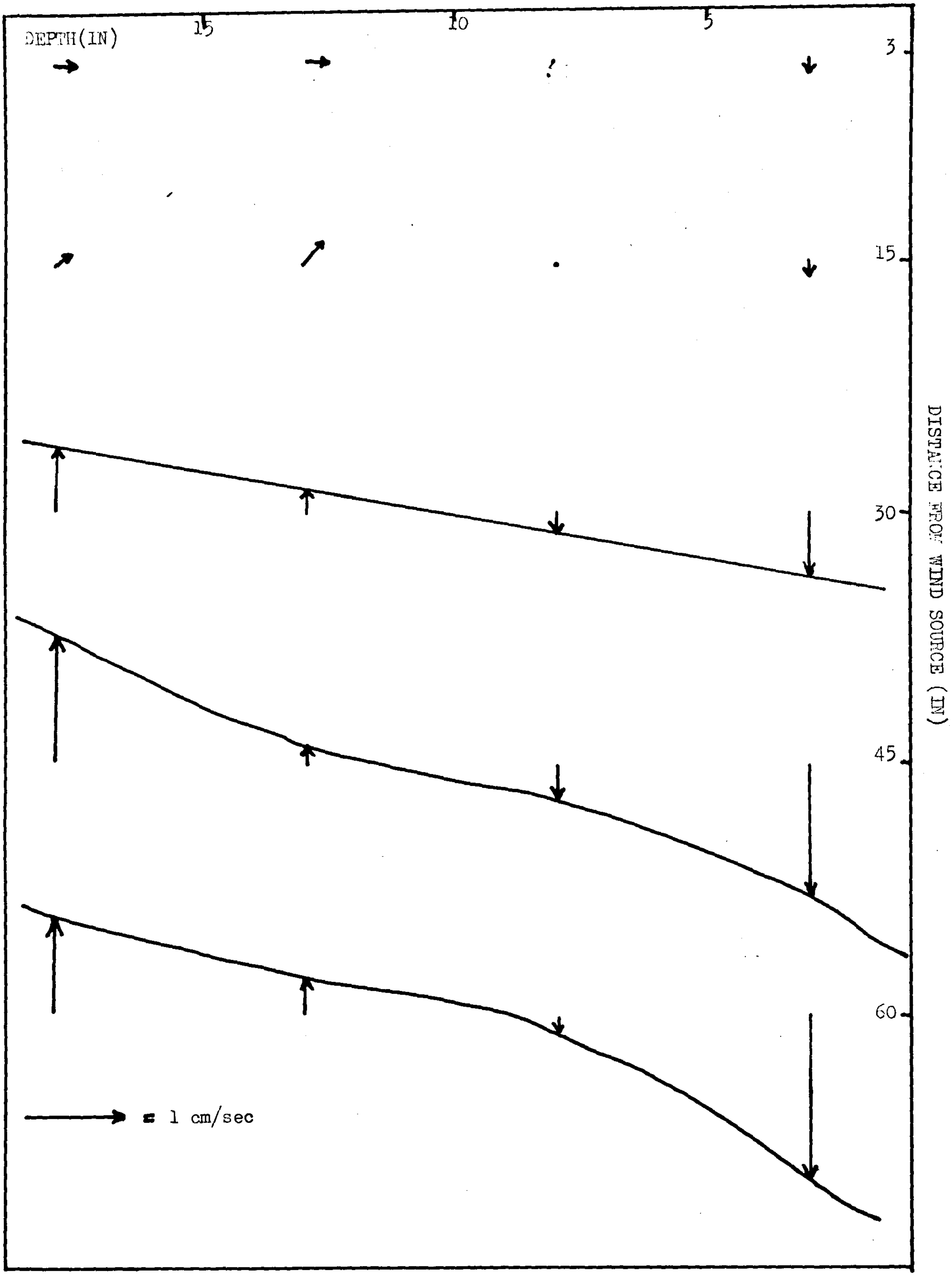


FIGURE 12, WAVE HEIGHT vs WIND SPEED

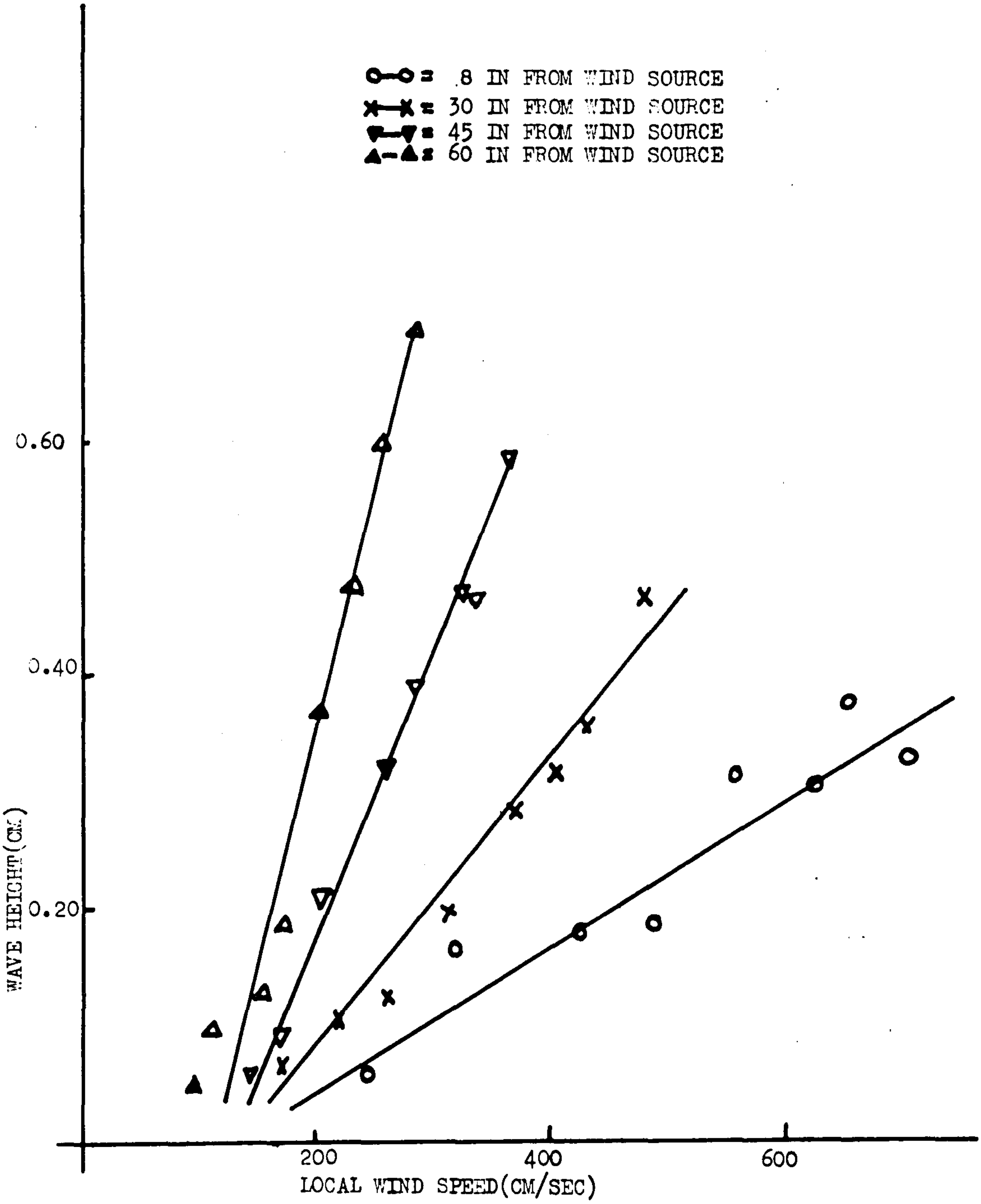
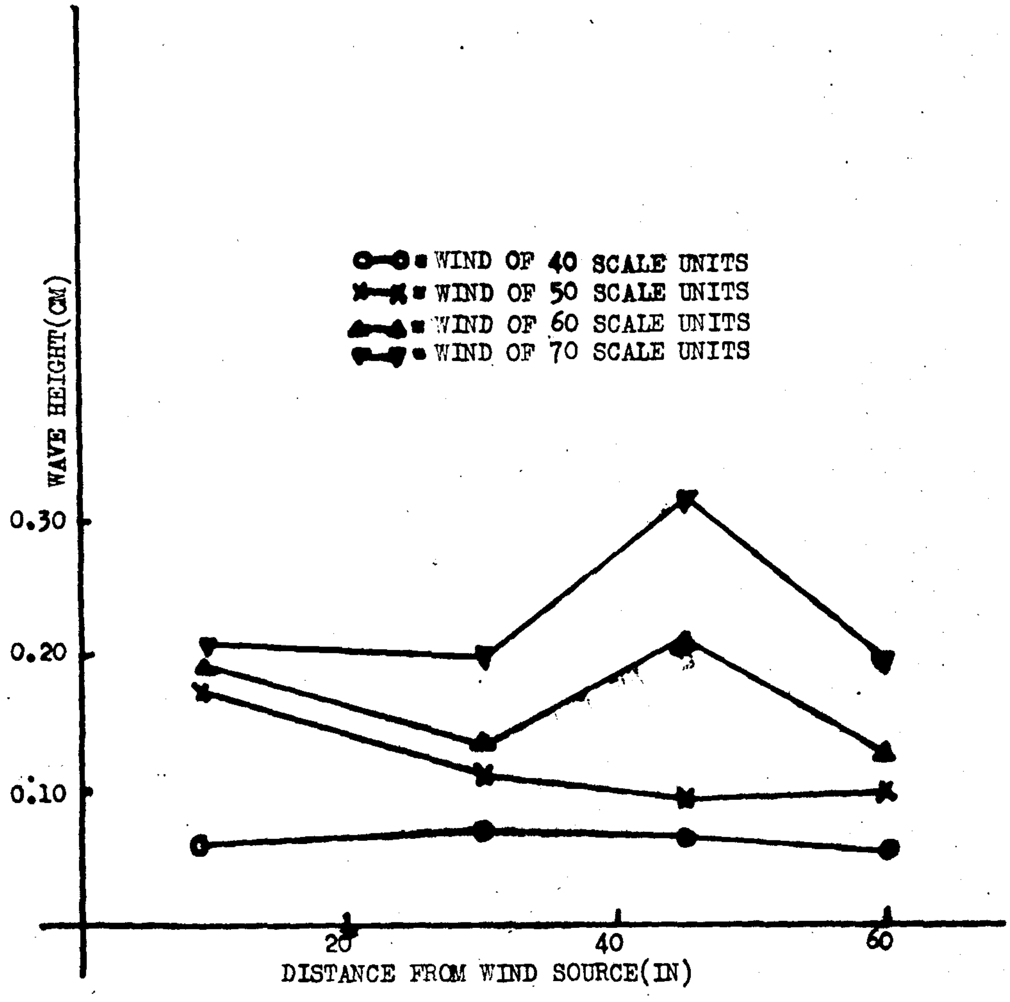


FIGURE 13. WAVE HEIGHT vs DISTANCE FROM WIND SOURCE



RECOMMENDATIONS FOR FUTURE RESEARCH

There were flaws in the experiment that should be corrected in any future work. The most significant of these is probably heat loss. The front of the working area of the wave tank was glass, and the rear was a metal partition that separated the water under investigation from the rest of the water in the tank. It seems fairly certain that some heat was lost through these two walls, but how much is not known. In any future work, the walls should be insulated. Also, the board placed over the tank to channel the air did not fit tightly. The decrease in wind velocity and air temperature with distance from the source could be reduced by installing gaskets along the board. With more accurate temperature control, heat-budget calculations might be possible.

Another source of error was the relative uncertainty of the thermistor location. The thermistor was pulled up through the water by hand and its location fixed about every five inches on the way up. A better way to move the thermistor might be to attach it to a constant speed motor and time its travel.

Currents seemed to play a large role at the higher wind speeds, and only a rough measurement of them was possible. One might inject dye at various places and then take timed motion pictures to measure the direction and magnitude of the currents.

Because of the similarity to the results of Tabata et. al., the indication of the linear increase of thermocline depth with wind speed in the range of wind values of 40 to 60 scale units should be investigated more thoroughly. This could be accomplished with the improvements suggested above.

The increase in depth of the thermocline at the leeward end might be avoided by using a much longer tank, and studying conditions far from the leeward end.

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13. ABSTRACT

An investigation was undertaken to examine the effects of wind waves upon a temperature gradient in a wave tank. The gradient was created by heating the surface water and cooling the bottom water. Temperature measurements were made with thermometers and a thermistor. The wind was measured with a pitot tube anemometer. The wind waves created a thermocline, and there was an indication of a linear correlation between the depth of the thermocline and the wind speed, which was similar to previous open-ocean work. A heat budget calculation was made, and it was found that the amount of heat in the water column remained almost constant.

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
WIND WAVES						
TEMPERATURE GRADIENT						

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